

UP: Have Observations Revealed a Variable Upper End of the Initial Mass Function?
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Upper End IMF Variations Deduced from HI-Selected Galaxies

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Abstract. Much of our understanding of modern astrophysics rest on the notion that the Initial Mass Function (IMF) is universal. Our observations of a sample of HI-selected galaxies in the light of H α and the far-ultraviolet (FUV) challenge this result. The flux ratio $F_{\text{H}\alpha}/f_{\text{FUV}}$ from these star formation tracers shows strong correlations with surface-brightness in H α and the R band: Low Surface Brightness (LSB) galaxies have lower $F_{\text{H}\alpha}/f_{\text{FUV}}$ ratios compared to High Surface Brightness (HSB) galaxies as well as compared to expectations from equilibrium models of constant star formation rate (SFR) using commonly favored IMF parameters. I argue against recent claims in the literature that attribute these results to errors in the dust corrections, the micro-history of star formation, sample issues or escaping ionizing photons. Instead, the most plausible explanation for the correlations is the systematic variations of the upper mass limit and/or the slope of the IMF. I present a plausible physical scenario for producing the IMF variations, and suggest future research directions.

1. Introduction

The assumption that the IMF is constant is commonly adopted in astrophysics. The basis for this assumption can be summarized as follows. Color-magnitude diagram (CMD) analyses of populous star clusters, where the IMF is easiest to measure, show that the upper end of the IMF has a slope close to the Salpeter (1955) value $\gamma = -2.35$, with cluster to cluster variations explainable by stochastic variations in the number of stars in each cluster (Kroupa 2001). Lada & Lada (2003, hereafter LL03) find that almost all star formation occurs in star clusters. Since clusters have a constant IMF and all stars form in clusters, then the IMF must be constant.

Recent studies (including Hoversten & Glazebrook 2008; Lee et al. 2009) indicate problems with this assumption. Our contribution to this field, Meurer et al. (2009, hereafter M09), has been particularly forthright in its challenge to a constant IMF. Here I review results from that study, present a scenario for the origin of the IMF variations and respond to critiques of our paper.

2. The SINGG and SUNGG surveys

Our results are based on two surveys: the Survey of Ionization in Neutral Gas Galaxies (SINGG; Meurer et al. 2006, hereafter M06) and it's sister Survey of Ultraviolet

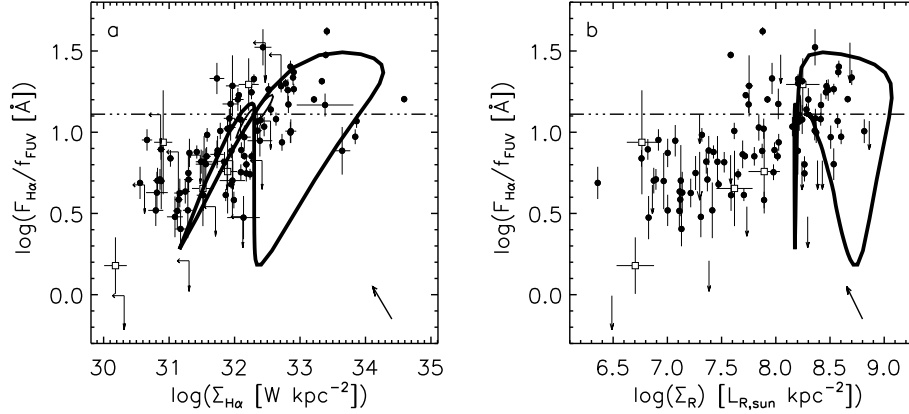


Figure 1. Our main result: $F_{\text{H}\alpha}/f_{\text{FUV}}$ correlates with optical surface brightness, Σ . Panels (a), (b) plot the effective surface brightness in H α and R band respectively. Downward and leftward pointing arrows indicate cases with H α signal to noise ratio < 2 . The diagonal arrow in the lower right corner of each panel represents the average effect of dust absorption, which has been removed. The broken horizontal line shows the $F_{\text{H}\alpha}/f_{\text{FUV}}$ value expected for a constant SFR population having a Salpeter IMF extending up to $100M_{\odot}$. The curves represent models for a “burst” (SFR increase - loops to the right) or “gasp” (SFR decrease - loops to the left) SFH. The SFH in each case has a constant base level with the burst or gasp having a Gaussian shape with fixed FWHM duration of 10 Myr. Two cases for the ratio of maximum to minimum SFR for each SFH are shown 2:1 and 100:1. Additional models are shown in M09.

emission in Neutral Gas Galaxies (SUNGG; Wong 2007). The parent sample of both of these is the HI Parkes All Sky Survey (HIPASS Meyer et al. 2004; Koribalski et al. 2004). Nearly 500 galaxies were selected from HIPASS for SUNGG so as to evenly populate the HI mass function with preferentially the nearest galaxies selected. Over 300 of these were imaged in H α and the R band. Nearly 150 galaxies from SUNGG were selected to be observed by GALEX in the FUV and NUV bands for SUNGG. 104 galaxies with complete optical and UV datasets were used in M09.

Our simple HI selection method means we do not suffer any of the common optical biases. This is illustrated in M06 where we show that all HI targets in our first data release correspond to H α emitting galaxies (in some cases multiple galaxies), and that all known morphologies of star-forming galaxies are represented. Similarly Hanish et al. (2006) demonstrate how our selection allows us to recover the cosmic SFR density of the local universe. These results demonstrate that our sample is not biased against any particular type of galaxy as long as it has HI. Hence, we can rule out selection effects as causing our results; this is an essential component of our claim that we found true IMF variations (see §3.2 below).

The ability to probe the IMF with two star-formation tracers was a major design feature of our surveys. H α emission traces the distribution of the ionizing O stars, with initial masses down to $M_{\star} \sim 20M_{\odot}$, while the vacuum UV emission detected by GALEX traces both O and B stars (initial masses $3M_{\odot} \lesssim M_{\star} \lesssim 20M_{\odot}$). The total luminosity of a star forming population is dominated by the vacuum UV and is fairly insensitive to the parameters governing the upper end of the IMF. The fraction of

ionizing light emitted, on the other hand, does depend strongly on the IMF parameters. Thus the ratio of $H\alpha$ to UV emission is very sensitive to the IMF.

3. The Results

Our key result is shown in Fig. 1 - the ratio of $H\alpha$ line flux to FUV flux-density $F_{H\alpha}/f_{FUV}$ varies strongly with optical surface brightness. In these plots, each point represents a single galaxy. The x -axis gives the face-on effective surface brightness Σ , while $F_{H\alpha}/f_{FUV}$, plotted on the y -axis, corresponds to the ratio integrated over an aperture large enough to encompass the entire galaxy. By using integrated quantities we avoid concerns about small-scale structure and evolution; it doesn't matter that ionizing photons may escape HII regions, nor that clusters dissolve, as long as the stars remain in the galaxy and the ionization happens in the galaxy. We find that $F_{H\alpha}/f_{FUV}$ also correlates with other quantities including morphology, luminosity and dynamical mass. The luminosity correlation was independently found in the 11HUGS sample as discussed by (Lee et al. 2009). Since Σ correlates with luminosity (Ferguson & Sandage 1988; Kauffmann et al. 2003), it is not surprising that $F_{H\alpha}/f_{FUV}$ correlates with both quantities. We find that the correlations with Σ are stronger and hence will concentrate on them (especially the Σ_R correlation). The LSB galaxies are most noteworthy in these panels. These are typically dwarf irregular (dI) galaxies. Their low $F_{H\alpha}/f_{FUV}$ ratios suggest a truncated IMF or steep γ . Next, I examine other factors that can affect $F_{H\alpha}/f_{FUV}$. By showing that these can not account for our results, we are left with IMF variations as the most likely explanation for the observed correlations.

3.1. Dust Attenuation

A key concern with any UV or optical study is dust attenuation. Our corrections for dust in the UV are based on the $IRX-\beta$ relation for SUNGG galaxies shown in Fig. 2a. Our calibration falls below the relationship found for starburst galaxies by (Meurer et al. 1999), and is similar to the relationship found in other samples of local normal galaxies (e.g. Seibert et al. 2005; Gil de Paz et al. 2007). In the optical, we employ a secondary correlation derived by Helmboldt et al. (2004) from integrated Balmer decrements measured in the Nearby Field Galaxy Survey (Jansen et al. 2000). Figure 2b (from M06, reproduced by permission of the AAS) shows that our optical dust correction can account for the relationship between the ratio of $H\alpha$ and FIR fluxes and the R luminosity for the SINGG galaxies detected by IRAS. Fig. 2 demonstrates that our dust corrections can account for the attenuation that ends up in warm dust emission.

The key arguments against dust causing our correlations are that (a) the typical correction ends up to be small compared to the scale of the correlations (as shown by the reddening vectors in Fig. 1), and (b) the correlations between Σ and $F_{H\alpha}/f_{FUV}$ exist even without any dust corrections. This was shown in Fig. 6 of M09, where the LSB end of the correlation is significantly below the fiducial $F_{H\alpha}/f_{FUV}$ level expected for a fully populated Salpeter/Kroupa IMF even before dust correction. Using a larger dust correction will move these galaxies further from the fiducial ratio, not closer.

Boselli et al. (2009, hereafter B09) tested dust corrections similar in form to ours. This produced stronger correlations of $F_{H\alpha}/f_{FUV}$ with other quantities in their sample than when they performed no corrections. They argued that this is not physically plausible and hence that such "statistical" corrections are unreliable and should not be used. While this is a legitimate concern, their problem does not affect our study. We find

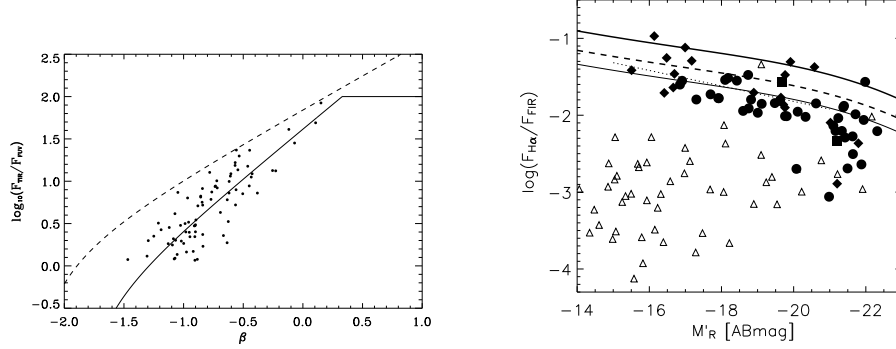


Figure 2. Tests of our dust absorption and re-emission model. Panel (a) (left) shows the ratio of total far infrared emission to that in the FUV plotted against the ultraviolet spectral slope, β , (derived from the FUV-NUV color) for the SUNGG galaxies also detected in the FIR by IRAS (Wong 2007). Our calibration of the global dust reddening relation is shown as the solid line. The calibration for starburst galaxies by Meurer et al. (1999) is shown as the dashed line. Panel (b) shows the ratio of $\text{H}\alpha$ and FIR fluxes plotted against R band absolute magnitude. Filled symbols mark IRAS detections, while triangles indicate IRAS non-detections as 3σ lower limits in $F_{\text{H}\alpha}/f_{\text{FIR}}$. The curves represent the application of a simple dust reprocessing models on stellar population models. The solid line is for a Salpeter IMF over a mass range of 1 - 100 M_{\odot} ; the dashed line is for the same γ but over the mass range of 1 to 30 M_{\odot} . The thin solid line and dotted line segment show fits to the data: the thick solid line shifted vertically and a simple linear fit respectively. Further details can be found in M06.

that the correlations after dust corrections are somewhat worse than the uncorrected correlations, as expected since the corrections are noisy and determined from independent quantities. Our derived average dust attenuation vector points in nearly the same direction as the relationship derived by Calzetti (2001, see Fig. 1 of M09), which is satisfying considering how coarse the corrections are. B09 go on to remove sources that do not have FIR fluxes from their sample. This results in a much weaker correlation and very few galaxies with low $F_{\text{H}\alpha}/f_{\text{FUV}}$. Dwarf galaxies, typically LSB, have very weak FIR emission even in deep Spitzer observations (Lee et al. 2009; Dale et al. 2009). By excluding galaxies without FIR emission, B09 are effectively throwing out the most interesting part of their sample.

3.2. Star Formation History (SFH)

Rapid changes in the SFR can lead to large changes in $F_{\text{H}\alpha}/f_{\text{FUV}}$. We used Starburst99 models (Leitherer et al. 1999) to test whether SFR variations could cause the observed correlations. Our models consist of a population forming stars at a constant rate with a Salpeter IMF over the mass range 0.1 to 100 M_{\odot} which then experiences a sudden increase (burst) or decrease (gasp) in the SFR. Further details of the model are given in M09. The results of the modeling are shown in Fig. 1. Panel (a) shows that strong changes in the SFR can result in large simultaneous variations in both $F_{\text{H}\alpha}/f_{\text{FUV}}$ and $\Sigma_{\text{H}\alpha}$. However, panel (b) shows that the effects on Σ_R are much smaller; neither the beginning of a gasp nor the end of a burst can give the correlated decrease in both Σ_R and $F_{\text{H}\alpha}/f_{\text{FUV}}$ needed to explain low $F_{\text{H}\alpha}/f_{\text{FUV}}$ galaxies. Since HI selection does

not preclude LSB galaxies with high $F_{H\alpha}/f_{FUV}$ (nor HSB - low $F_{H\alpha}/f_{FUV}$ galaxies), we can not hide galaxies from our selection during inopportune phases of the star formation cycle. If SFH causes the low $F_{H\alpha}/f_{FUV}$ cases, then all the LSB galaxies in nearby universe are simultaneously going through a sharp decrease in the SFR. Such synchronicity is implausible and allows us to rule out SFH as the cause of the observed correlations. Similarly, Hoversten & Glazebrook (2008) find that the spread of $H\alpha$ EW versus optical colors in SDSS galaxies can only be explained by a bursty SFH if there is an implausible synchronicity in the timing of the bursts, and thus ruled out a variable SFR as causing their results.

Boselli (at this conference and in B09) argues that variations in the “micro-history” of star formation can explain the large range of $F_{H\alpha}/f_{FUV}$. However, his toy-model only considers the ratio $F_{H\alpha}/f_{FUV}$ and not surface brightness. This does not address the correlations which are at the heart of the problem. Instead he suggests the experiment of considering a dwarf galaxy with and without the 30 Dor region. The actual model used in B09 consists of regularly spaced bursts with no star formation between bursts. The inter-burst period they require to produce the $F_{H\alpha}/f_{FUV}$ distribution would also produce many $H\alpha$ non-detections which is inconsistent with SINGG results (M06). The dwarf galaxies usually associated with bursts are Blue Compact Dwarfs (BCD). Meurer et al. (1999) show that the bursts in BCDs amount to at best a factor of a few change in the SFR. Thus an appropriate model for the SFH in dwarf galaxies is the factor of two burst/gasp model, shown as the thin lines in Fig. 1, which are barely discernible in these plots because the excursions in $F_{H\alpha}/f_{FUV}$ versus Σ are relatively small. Hypothetical extreme bursts are required to explain the $F_{H\alpha}/f_{FUV}$ excursions, and even then, the correlation with Σ_R is not explained as noted above.

3.3. Escaping Ionizing Radiation

Using $H\alpha$ as a star forming indicator implicitly assumes that all ionizing photons are absorbed by the ISM. The observed $F_{H\alpha}/f_{FUV}$ correlations could occur if the escape fraction of ionizing photons, f_{esc} , inversely correlates with Σ . This scenario would require $f_{esc} > 0.5$ to explain the galaxies in the lowest quartile of $F_{H\alpha}/f_{FUV}$. While this is a large effect, no attempt has been made to observe emission with a rest $\lambda_0 < 912\text{\AA}$ in LSB galaxies, so it is not yet possible to formally rule out this scenario. Escaping ionizing photons are the preferred explanation of the low $F_{H\alpha}/f_{FUV}$ ratios given by Hunter et al. (2010). They also imply that some $H\alpha$ is missed from the observations because it is below the $\Sigma_{H\alpha}$ detection limit.

The detection limit concern is easily dismissed. Our measurements and upper limits are state of the art and accurate to within the error bars shown, even when $H\alpha$ is not detected in some individual pixels, because those pixels are within the large elliptical apertures employed in our analysis (M06). A large f_{esc} also seems unlikely for two reasons. First, the problem cases are the LSB galaxies, and these typically have a higher ISM content (larger M_{HI}/L_B) and puffier disks than the larger spiral galaxies. Hence, they should be able to retain their ionizing photons better. Second, CMDs of the nearest galaxies indicate that LSB galaxies typically are deficient in O stars (e.g. Young et al. 2007) compared to HSB irregulars and BCDs (e.g. Annibali et al. 2008). Since such studies usually have been on a galaxy per paper basis, then the assumption of a fully sampled Salpeter IMF can fool any team of astronomers to find that their particular galaxy has a gasping SFH. A better approach would be to obtain uniform high quality HST data of many nearby galaxies and then compare CMDs as a function

of Σ . If the sample is large enough, galaxy to galaxy variations will average out and an effective IMF can be deduced. The ANGST team have obtained such a dataset (Dalcanton et al. 2009) and are well poised to do such a study.

4. What Causes Upper End IMF Variations?

4.1. Cluster Versus Field Star Formation

As noted in §1, much of the support for a constant IMF rests on the notion that all star formation occurs in star clusters. However, $H\alpha$ and UV images of galaxies show the majority of the light is diffuse rather than being in discernible clusters or HII regions. With SINGG we find that on average $\sim 40\%$ of the $H\alpha$ emission is in HII regions while the rest is diffuse (Oey et al. 2007). In UV and U band light, the fraction of light that is in compact clumps (presumably clusters) is typically $\sim 20\%$ for starbursts (Meurer et al. 1995) and only a few percent for normal galaxies (Larsen & Richtler 2000); the vast majority is diffuse. The dominant diffuse population has low $F_{H\alpha}/f_{FUV}$ (Hoopes et al. 2001) and a UV spectrum dominated by B stars, whereas the young “super star clusters” typically have O star rich spectra (Tremonti et al. 2001). The disparity between cluster and field is typically ascribed to infant mortality (e.g. Tremonti et al. 2001; Pellerin et al. 2010). The main problem with this scenario is that naively one would expect infant mortality to be stronger in the dense environment of starbursts than in normal and LSB galaxies, whereas the results of Meurer et al. (1995) and Larsen & Richtler (2000) indicate that clusters are *more* prevalent and thus last longer in starbursts.

The interpretation from LL03 that all star formation occurs in clusters is based on an expansive redefinition of the term “cluster” to include objects that are unbound at birth (when they shed their natal gas). Better terms for these unbound objects are the older terms “group” and “association”, which now seem to be largely neglected by the extragalactic astronomical community. However, it is important to retain such a distinction, because it is crucial in the physics of high mass star formation. Simulations indicate that high mass stars can form readily in dense *bound* clusters where proto-stars can quickly build-up to high mass by competitive accretion (Bonnell et al. 2003, 2004). Alternatively, Krumholz & McKee (2008) show that high mass stars can form efficiently in a top-down fashion when the ISM density is very high, because then fragmentation is inhibited. In either scenario, the physics is different for star formation in dense clumps compared to low density or unbound objects. Recent large area infrared surveys reveal a significant “distributed mode” of star formation comprising $\sim 30\%$ of star formation in the solar neighborhood (Allen et al. 2007; Megeath et al. 2009). This star formation, combined with the large fraction of unbound objects that LL03 refer to as clusters, is likely to make the majority of the diffuse UV emission in galaxies.

4.2. Our Scenario

We posit that the $F_{H\alpha}/f_{FUV}$ ratio variations arise from the difference between star formation in bound clusters and the field. Bound clusters need a dense cold molecular ISM to form. The fraction of the total ISM that goes into this phase is set by the hydrostatic pressure (McKee & Ostriker 1977; Blitz & Rosolowsky 2006), which also determines how tightly bound clusters are when they form (Elmegreen & Efremov 1997; Elmegreen 2008). Stars dominate the disk plane potential, thus largely setting the pressure. This results in the correlation with Σ_R which also measures the disk plane mass

density. A high mass density disk results in high pressure ISM, with a larger fraction of its mass in cold dense molecular clouds. These form dense bound clusters that are rich in massive O stars, and hence a high $F_{\text{H}\alpha}/f_{\text{FUV}}$. Conversely, a low mass density disk will have lower Σ , lower pressure, and less formation of bound clusters relative to field stars and unbound objects. This results in a low $F_{\text{H}\alpha}/f_{\text{FUV}}$.

4.3. Implications

A variable IMF has numerous major implications. Star formation surveys that adopt a constant IMF are likely to get a biased result depending on the tracer they use and the pressure of the ISM. UV based SFRs should be more accurate than those derived from $\text{H}\alpha$ (Lee et al. 2009). Similarly, a variable IMF throws in to doubt the basis for measuring the SFH from CMDs using the tip of the main sequence as a clock. Finally a variable IMF provides an alternative explanation for the mass metallicity relationship (Tremonti et al. 2004). Instead of requiring a galactic wind to remove excess metals from dwarf galaxies, a truncated IMF means that they may not have made them in the first place.

5. Conclusions and Future Work

The correlation between global $F_{\text{H}\alpha}/f_{\text{FUV}}$ and the surface brightness of galaxies provides strong evidence that the IMF is varying, and suggests that the underlying cause is the hydrostatic pressure of the ISM which regulates the phase balance of the ISM and consequently the efficiency of the highest mass stars to form. As discussed throughout this meeting (and noted above) a variable IMF has major implications for many branches of astrophysics

While I believe that the preponderance of evidence clearly demonstrates the variable nature of the IMF, the astronomical community, as a whole, is not yet convinced. One common thread in studies showing IMF variations is the use of $\text{H}\alpha$ as a star forming indicator. It would be good to confirm these results using other methods, such as CMD studies. Deep CMD studies of large samples of nearby galaxies (e.g. ANGST) are also critical for determining how far down in mass the IMF variability goes. Such studies would also provide useful tests of the IGIMF hypothesis (Weidner & Kroupa 2005; Pflamm-Altenburg et al. 2009) which makes predictions on the form of the galaxy wide IMF. Cases of high $F_{\text{H}\alpha}/f_{\text{FUV}}$, well above Salpeter expectations, as seen in our work and that of Gunawardhana (this meeting), are also interesting. The highest values may be pushing beyond what models can achieve by just adjusting the upper mass limit or γ , and may instead require truncating the lower end of the IMF at values above $3 M_{\odot}$. Such a short-wick IMF is similar to what is required at high redshift to explain differences between the cosmic SFR density and the mass assembly history (Davé 2008; Wilkins et al. 2008b,a). Hence high $F_{\text{H}\alpha}/f_{\text{FUV}}$ galaxies may be good analogs to high redshift galaxies.

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